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The determination of dust cloud altitudes from a satellite using hyperspectral measurements in the gaseous absorption band

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An approach to derive dust layer optical thickness and top height using top-of-atmosphere (TOA) reflectance in the oxygen A-band is introduced. The algorithm is similar to that developed by the authors for the case of water clouds. It is based on the fitting of spectral TOA reflectance measurements in the narrow band around 760 nm using results of the exact radiative transfer calculations for a given dust layer model. The accuracy of the technique with respect to the uncertainty in *a priori* assumption of the dust single-scattering albedo is discussed. The algorithm is applied to satellite hyperspectral measurements over the Atlantic Ocean.

1. Introduction

Dust outbreaks from deserts are of considerable interest for climate, pollution and ocean productivity studies. Therefore, one needs to characterize desert dust plumes in terms of their extent, speed and direction of propagation, the dust deposition rate, the aerosol columnar mass concentration, average sizes of particles, their chemical composition and also the plume altitude. The information on dust plume geometrical boundaries is of importance for aircraft safety, climate studies and for cloud formation and dissipation processes. Dust outbreaks and volcanic eruptions influence atmospheric chemical composition and dynamics (Kondratyev and Varotsos 1995).

The characterization of desert dust on a global scale can be carried out only using satellite measurements (e.g. observations from a geostationary orbit). Satellite pictures of desert dust plumes resemble those of clouds with respect to the high reflectivity of dust, although the colour of dust as seen in satellite browse images is not white. It is brownish and is determined by the chemical composition and origin of the desert dust grains.

The satellite retrieval algorithms of dust characteristics based on backscattered solar light measurements are not trivial. First, the advanced cloud screening algorithms must be used for satellite desert-dust studies. The cloud screening, based on the height of the plume and on the reflectivity thresholds, cannot be applied because dust-plume reflectivities and heights resemble those of low clouds. Clearly, colour and thermodynamic state indices (e.g. determined using hyperspectral measurements) must be used to distinguish desert dust from a cloud or the cloud–desert-dust mixture (Kokhanovsky *et al.* 2009). The pixels with a simultaneous cloud and desert dust presence must be filtered out because corresponding retrievals for mixed states are not sufficiently advanced. Yet another problem is the assumption on the shape of particles

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to be used in the retrieval procedure. The shape of dust grains is poorly characterized and the assumption of spherical dust grains leads to considerable errors in the retrieved dust characteristics (e.g. dust optical thickness (DOT)). This is due to the high sensitivity of backscattered light intensity to the shape of particles. In particular, smaller concentrations of non-spherical dust grains can produce the same backscattered light intensity compared to larger concentrations of spherical particles of the same size and chemical composition. This can lead to wrong estimations of dust flux to ocean based on satellite measurements of reflected solar light.

Notwithstanding the problems described above, there are numerous studies of desert-dust properties using satellite measurements. In particular, Kaufman *et al.* (2005) (see also the references therein) reported their investigations of Saharan dust transport and deposition using the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra spacecraft. The authors studied the total flux of transported matter from Africa to the Atlantic Ocean and found that 240 ± 80 Tg of dust is transported annually from Africa to the Atlantic Ocean and Amazon Basin. Clearly, the desert-dust reflectance is highly sensitive to the dust columnar concentration with higher values for larger concentrations. This feature of dust reflectance was used by authors for the estimation of the net dust flux and related dust quantities.

The enhanced light reflectivity for pixels contaminated by dust and clouds as compared to a clear-sky case over low-reflecting ground (e.g. ocean) is often used for the determination of cloud and DOT (Kokhanovsky 2006). The determination of the scattering layer geometrical thickness and the position of cloud boundaries (especially lower ones) from a satellite is a much more difficult task. One can use the stereoscopy technique (Kahn *et al.* 2007) or lidar measurements (Huang *et al.* 2007) to get the dust plume height. In addition, hyperspectral measurements in the gaseous absorption band can be used (Rozanov and Kokhanovsky 2004). Indeed, measurements outside the gaseous absorption band are almost insensitive to the scattering layer height. The physical principle behind the dust or cloud-top altitude retrieval in the gaseous absorption band (e.g. O_2 and CO_2) is based on the fact that a scattering layer screens the gas under the cloud, thus enhancing the reflectivity in the gaseous absorption band as detected on a satellite. Additionally, effects of the enhancement of the gaseous absorption inside the cloud due to multiple light scattering effects are of importance. A review of corresponding papers and the theory behind the retrieval algorithms is described in great detail by Rozanov and Kokhanovsky (2004). For retrievals of the scattering layer height, the oxygen absorption A-band is usually used (Yamamoto and Wark 1961).

The task of this paper is twofold. First of all, we adapt our water/ice cloud-top height retrieval algorithm SACURA (Rozanov and Kokhanovsky 2004) to the specific task of the dust-top height (DTH) observation from space. This requires two types of modification. First, the phase function must be modified because light scattering by water droplets differs considerably from that of dust and, secondly, the asymptotic theory (Kokhanovsky 2006) we used in cloud retrievals is substituted by exact radiative-transfer calculations for the specific case of a desert dust considered in this paper. This is because the optical thickness of dust layers is usually smaller than 5, and, therefore, asymptotic calculations, as described by Rozanov and Kokhanovsky (2004), cannot be applied to the problem at hand. The second aim of this paper is to perform retrievals of DTH for synthetic and satellite top-of-atmosphere (TOA) reflectivities and also study their sensitivity to the unknown value of the dust single-scattering albedo (SSA).

2. Theory

2.1 *DTH retrieval algorithm*

The dust layer height is retrieved in this work using the linearization technique, as described by Rozanov and Kokhanovsky (2004) and Rozanov *et al.* (2007). In particular, the reflectivity (Kokhanovsky 2006) $R = \pi I/\mu_0 E$ (where μ_0 is the cosine of the incidence angle, E is the solar irradiance at the TOA and I is the reflected light intensity) measured by a spectrometer onboard a satellite in the gaseous absorption band is presented as:

$$R(h) = R(h_0, h_{\mathrm{b}0}, \tau_0) + [h - h_0]W(h_0) + [h_{\mathrm{b}} - h_{\mathrm{b}0}]W(h_{\mathrm{b}0}) + [\tau - \tau_0]W(\tau_0), \tag{1}$$

where h_0 is the assumed DTH and h is the 'true' DTH, h_{b} and h_{bo} are 'true' and assumed dust bottom heights (DBHs) and τ and τ_0 are 'true' and retrieved DOTs, respectively. The values of $R(h_0, h_{\mathrm{b}0}, \tau_0)$ can be calculated using the exact radiative-transfer theory for the assumed values of DTH, DBH and DOT retrieved outside the gaseous absorption band. The value of $W(x_0)$ is given by the derivative $\mathrm{d}R/\mathrm{d}x$ at the point $x = x_0$ and can be calculated using various numerical techniques, e.g. the finite-difference technique. It will be assumed in this work that the dust cloud lower boundary coincides with the underlying ground altitude. This is often the case because dust clouds, unlike water clouds, originate at the ground. Then, equation (1) is simplified to:

$$R(h) = R(h_0) + [h - h_0]W(h_0), \tag{2}$$

where we have also accounted for the fact that the DOT is found outside of the gaseous absorption band. The value of the DTH is found by minimization of the function:

$$f(\lambda, h) = R(h) - R(h_0) + [h - h_0]W(h_0), \tag{3}$$

where λ is the wavelenght $R(h)$ is the measured TOA reflectance and $R(h_0)$ is the modelled reflectance for an assumed value of the DTH equal to h_0. The corresponding iterative procedure is stopped when the calculated and measured spectra inside the oxygen A-band coincide within an *a priori* assumed tolerance errors for the spectral fit. We do not use the finite-difference technique to find the derivative $W(h_0)$. Instead, for the calculation of the derivative $W(h_0)$, we apply the approach based on the adjoint radiative-transfer equation developed by Rozanov (2006) and Rozanov *et al.* (2007). This increases the speed of calculations considerably. Details of the derivations are given in the papers listed above. In particular, the derivative at $h = h_0$ is found using the following integral (Rozanov *et al.* 2007):

$$\frac{\mathrm{d}R}{\mathrm{d}h} = \int\limits_{4\pi} \mathrm{d}\Omega[w_{\mathrm{h}}(z_2, \Omega) - \bar{w}_{\mathrm{h}}(h_0, \Omega)], \tag{4}$$

where $\mathrm{d}\Omega = \sin\vartheta \mathrm{d}\vartheta \mathrm{d}\varphi$ is the elementary solid angle, ϑ is the zenith angle, ϕ is the azimuthal angle and $\Omega(\vartheta, \varphi)$ is the corresponding solid angle, which characterizes the light-beam propagation direction. In addition, it follows that (Rozanov *et al.* 2007):

$$\bar{w}_{\mathrm{h}}(h_0, \Omega) = \tfrac{1}{h_0} \int\limits_{z_1}^{z_2} w_{\mathrm{h}}(z, \Omega)\mathrm{d}z, \tag{5}$$

where

$$w_{\mathrm{h}}(z,\Omega) = \left[\frac{\omega_0(z)}{4\pi}\int_{4\pi} p(z,\Omega,\Omega')I(z,\Omega')\mathrm{d}\Omega' - I(z,\Omega)\right]k_{\mathrm{ext}}^{\mathrm{d}}(z)I^*(z,\Omega), \qquad (6)$$

$\omega_0 = k_{\mathrm{sca}}^{\mathrm{d}}/k_{\mathrm{ext}}^{\mathrm{d}}$ is the SSA, $p(z,\Omega,\Omega')$ is the dust phase function, which gives the conditional probability fo light scattering the solid angle Ω' to the direction specified by the solid angle Ω $k_{\mathrm{ext(sca)}}^{\mathrm{d}}$ are dust extinction (scattering) coefficients, respectively, I and I^* are solutions of the direct and adjoint radiative-transfer equations (Rozanov 2006) and z_1 and z_2 are lower and upper boundaries of the dust layer, respectively. In this work, it is assumed that local optical characteristics do not depend on the position in the dust cloud. It is also assumed that the lower boundary of the dust layer coincides with the ground surface height, and we need to find $z_2 = h_0 + z_1$, where z_1 is the known surface height (e.g. from the ground height database GTOPO30 (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html). The inverse problem can be formulated in such a way that the value of z_1 is also searched by the algorithm (Rozanov and Kokhanovsky 2004). However, the information content of measurements often does not permit an accurate simultaneous retrieval of both DBH and DTH. Therefore, it is of advantage to fix the dust lower-boundary height in the retrieval procedure. Fortunately, the variability of the lower dust-boundary position is smaller than that for water and ice clouds.

In addition, in the retrieval procedure, one must assume the dust phase function and the dust SSA ω_0. The value of ω_0 for dust is close to one in the oxygen A-band (Moulin *et al.* 2001). However, there is some variability of the SSA depending on the dust origin. Therefore, it is of importance to understand how inaccuracy in the assumed value of ω_0 influences the results of retrievals. This is considered in §3.

2.2 *DOT retrieval algorithm*

The DOT τ can be determined from measurements outside the absorption band. Equation (1) is simplified to the following form outside the gaseous absorption band:

$$R(\tau) = R(\tau_0) + [\tau - \tau_0]W(\tau_0), \qquad (7)$$

where τ_0 is the assumed DOT and the derivative $W(\tau_0)$ is defined in a similar way as described above. Namely, it follows (Rozanov *et al.* 2007):

$$W_\tau \equiv \frac{\mathrm{d}R}{\mathrm{d}\tau} = \int_{4\pi} \mathrm{d}\Omega \bar{w}_\tau(h_0,\Omega), \qquad (8)$$

where

$$\bar{w}_\tau(h_0,\Omega) = \frac{1}{h_0}\int_{z_1}^{z_2} w_\tau(z,\Omega)\mathrm{d}z \qquad (9)$$

and

$$w_\tau(z,\Omega) = \left[\frac{\omega_0(z)}{4\pi}\int_{4\pi} p(z,\Omega,\Omega')I(z,\Omega')\mathrm{d}\Omega' - I(z,\Omega)\right]I^*(z,\Omega). \qquad (10)$$

The application of the scheme described above enables the determination of both desert dust-cloud optical thickness and desert-dust plume-top height, and, therefore, the dust geometrical thickness. The dust extinction coefficient can also be estimated in the framework of the proposed forward model, which includes the following assumptions:

- the lower dust cloud boundary coincides with the underlying ground altitude;
- the SSA of dust is fixed (0.99) in this work;
- the phase function is not derived, but assumed (calculated using the Monte Carlo code as described below);
- the vertical and horizontal inhomogeneity of the dust layer is neglected;
- the possible influence of sub-pixel clouds is neglected; and
- the ground surface albedo is assumed.

All these assumptions, if not true, can bias results. Therefore, future research must be concentrated on their relaxation, e.g. using synergetic measurements of different satellite instruments and the preparation of robust cloud-screening algorithms.

The next section is aimed at the application of the algorithm to synthetic data obtained using the scalar radiative-transfer code SCIATRAN (Rozanov *et al.* 2005). This enables better understanding of the sensitivity of the retrieval technique to the unknown values of the assumed parameters, in particular, the SSA. Section 4 is aimed at the application of the algorithm to satellite data.

3. Numerical experiments

The retrieval technique described above was applied to the determination of the DOT and DTH using synthetic spectra of backscattered solar light in the oxygen A-band. Examples of corresponding spectra for an assumed surface albedo of 0.05 are given in figure 1. Calculations of the normalized TOA radiance $i = \pi I/E_0$ shown in figure 1 have been performed assuming $\omega_0 = 0.99$, and the phase function is plotted in figure 2. Here, I is the reflected light radiance and E_0 is the irradiance at the TOA assumed to be equal to π in the calculations. The phase function was calculated assuming the fractal grain model, as described by Macke *et al.* (1996) at the refractive index 1.53–0.008i and an effective radius of 20 μm and wavelength of 0.55 μm. The choice of the phase function is rather arbitrary. Therefore, in future one must constrain this function using multi-angle polarization measurements. Note that most modern aerosol retrieval algorithms are based on the assumption of a single typical phase function. The phase function shown in figure 2 is characteristic for dust aerosols because it has a flat behaviour in the backward region and also has increased lateral scattering (as compared to spherical scatterers). The simulation of light interaction with a fractal dust grain was performed using geometrical optics Monte Carlo calculations, as described by Macke *et al.* (1996). The statistical noise of the Monte Carlo calculations was removed from the final result using high-frequency filtering.

It follows from figure 1 that the reflectance in the oxygen A-band is indeed sensitive to the DTH. Dust layers positioned at lower altitudes produce deeper absorption features in the spectral reflectance compared to high-altitude dust outbreaks. The value of the DOT is found using measurements at 758 nm, where there is no need to know the DTH in the retrieval procedure (see figure 1). The result of DTH retrieval is illustrated in figure 3 as a function of the retrieved aerosol optical thickness for an assumed SSA = 1.0 (triangles), 0.99 (circles) and 0.98 (squares). The forward calculations of the synthetic spectra were performed at $\omega_0 = 0.99$ using SCIATRAN (Rozanov *et al.* 2005). Figure 3 confirms a high accuracy of the algorithm independently on the assumption on the value of the dust SSA in the range 0.98–1.0.

Generally, the retrieval error ε increases with DOT because small deviations of SSA from 1.0 are of a greater importance for radiative transfer at larger DOTs. However, ε remains quite small for all considered cases. The overestimation of dust SSA leads to

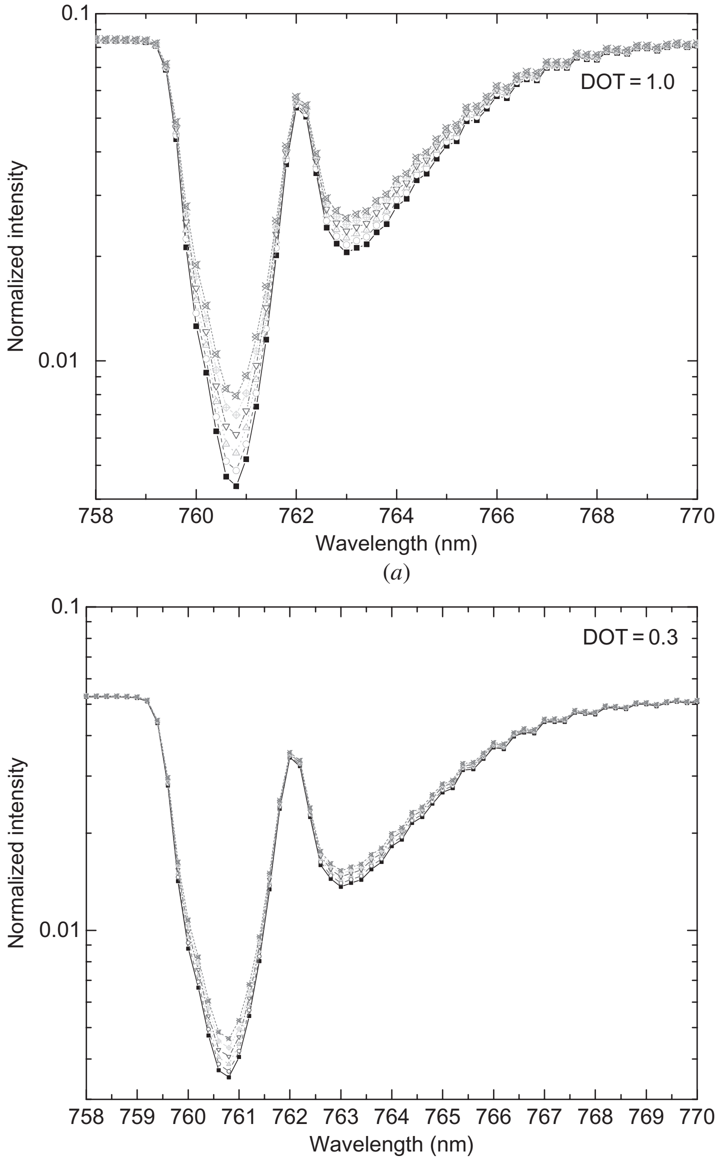


Figure 1. TOA normalized radiance over the dust aerosol with a DTH (lower lines 1,2,3,4,5, and 6 km correspond to around 761 nm smaller DTH) at SSA = 0.99: (*a*) DOT = 1.0 and (*b*) DOT = 0.3. The results were obtained for the nadir observation and the solar zenith angle equal to 60° using SCIATRAN (Rozanov *et al.* 2005). The surface albedo was assumed to be equal to 0.05.

the overestimation of DTH in most cases (see figure 3). The opposite is true for too low values of ω_0 in the retrieval procedure. The absolute error of the retrievals $\Delta = h_{\mathrm{retr}} - h_{\mathrm{true}}$ is shown in figure 4 as a function of the DTH. It follows that the errors increase with DTH in most cases, if the assumed dust SSA differs from the actual value of ω_0 used in the forward calculations.

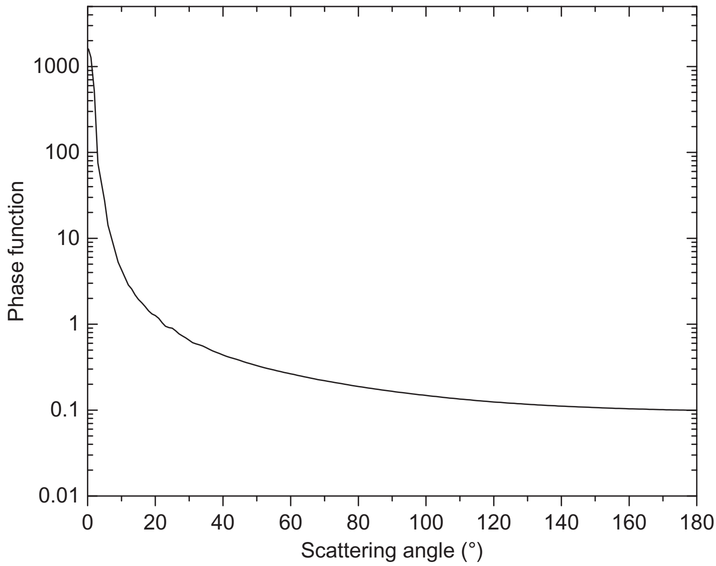


Figure 2. Phase function of dust used in the retrieval procedure. The phase function was calculated using the fractal dust grain model.

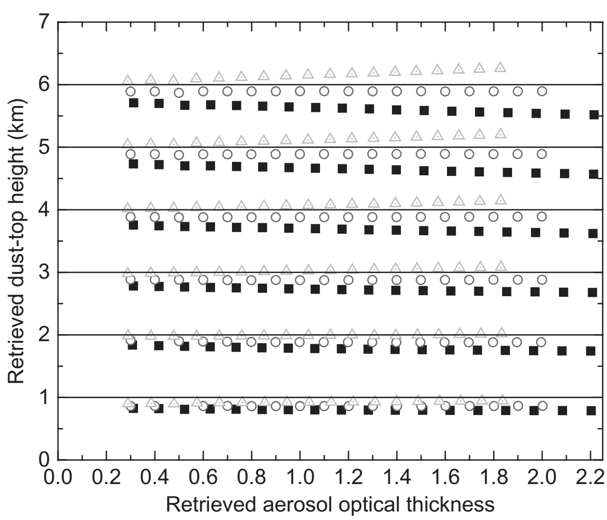


Figure 3. Dependence of the retrieved DTH on the retrieved aerosol optical thickness. Lines give the position of the 'true' DTH. Circles give the results for the case when the single scattering albedo for the forward calculation is equal to that assumed in the inversion procedure (SSA = 0.99). Squares correspond to the value of SSA assumed in the inversion procedure equal to 0.98 and triangles correspond to the case of SSA = 1.0, while the 'true' SSA is equal to 0.99. The results were obtained for the nadir observation and the solar zenith angle equal to 60°. The surface albedo was assumed to be equal to 0.05.

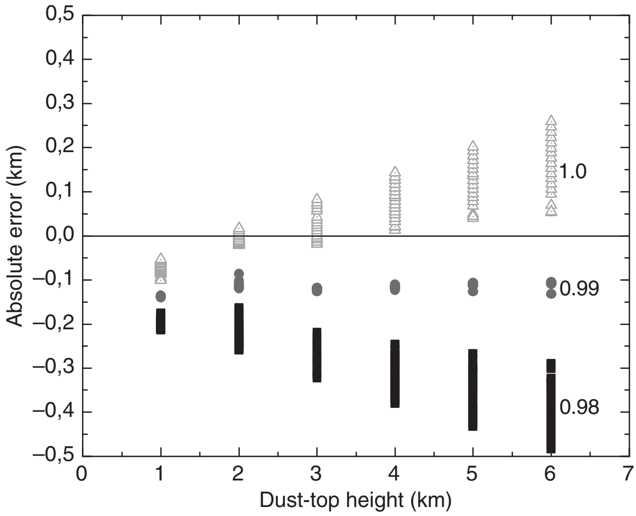


Figure 4. Absolute error of the DTH determination for different values of SSA and DOT. Triangles, SSA = 1.0; circles, SSA = 0.99; squares, SSA = 0.98.

Errors do not exceed 150 m for the case of retrievals with exactly known SSA. Theoretically, there should be no errors, if the same SSA (e.g. 0.99) is used in the retrieval procedure as for the forward-model calculations. The error is solely because, in the retrieval procedure, the simplified treatment of the atmosphere with a reduced number of layers and interpolation between them is used. This enables a drastic increase in the speed of the retrievals procedure.

Values of Δ are below +300 m for the overestimated SSA and smaller than 500 m (underestimation) for the case of too low values of SSA assumed in the retrieval process (see figure 4). In the retrievals of DTH shown in figure 3, the retrieved values of DOT at 758 nm were used. The accuracies of the corresponding DOT retrievals are demonstrated in figure 5. Too large values of ω_0 lead to underestimation of the DOT. The opposite is true for too small values of the SSA used in the retrieval process. This also follows from the single scattering approximation where $R \sim \omega_0 p(\theta)\tau$ (θ is the scattering angle) and, therefore, $\tau \sim R/(\omega_0 p(\theta))$, which also signifies the importance of having accurate phase function in the retrieval algorithm (von Hoyningen and Posse 1997).

One concludes that the retrievals are only weakly sensitive to ω_0 at small τ. However, uncertainty in the SSA leads to larger errors at larger τ (see figures 5 and 6), which is due to multiple light-scattering effects. Fortunately, the variability of the dust SSA is small in the oxygen A-band (e.g. compared to the ultraviolet) and the assumed value of 0.99 is representative for many cases (Moulin *et al.* 2001, von Hoyningen-Huene *et al.* 2009). Moreover, the DOT is rarely above 1, therefore, errors in the SSA influence results insignificantly (see, for example, figures 5 and 6). Errors in the assumed phase function can significantly bias results for the DOT. In particular, the model of spherical particles cannot be used in retrievals, as discussed by von Hoyningen-Huene and Posse (1997). The retrievals of cloud-top height are quite robust with respect to the errors in the retrieved DOT. We found, using numerical experiments, that overestimation of the DOT by 50% in the satellite retrieval procedures leads to an underestimation of the DTH by 0.3–0.4 km, and its underestimation by the same amount leads to an overestimation of the DTH by 0.3–0.6 km (at a 'true'

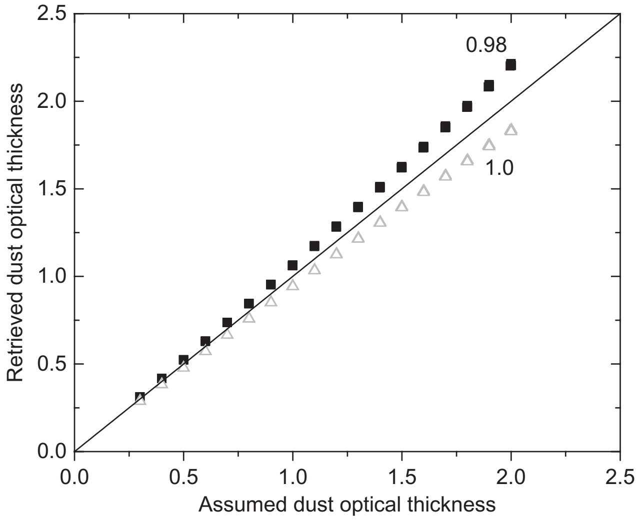


Figure 5. Retrieved DOT as a function of the 'true' optical thickness.

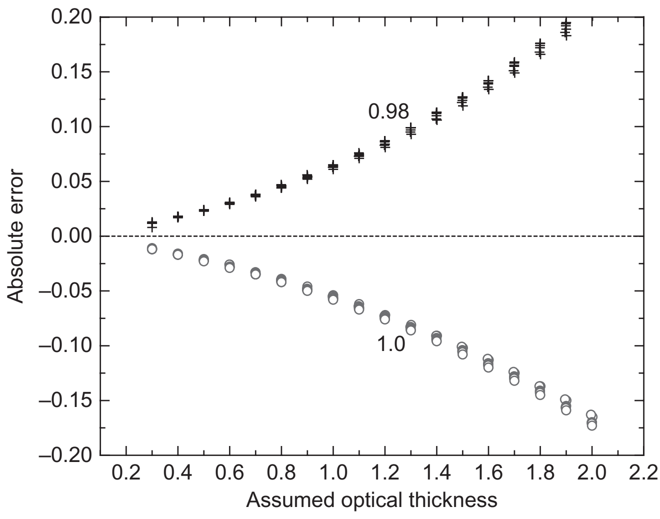


Figure 6. Absolute error of the retrieved DOT as a function of the assumed optical thickness at SSA = 0.98 (pluses) and SSA = 0.99 (circles).

DTH of 4 km and a DOT in the range 0.3–2.0). These are comparatively low errors, especially taking into account that the errors of the DOTs are usually in the range of 20%. The retrievals using oxygen A-band spectrometry are especially robust over the ocean because the reflectance of light from the ocean in the near-infrared, where oxygen A-band is located, is very low. Satellite retrievals of the DTH over the Atlantic Ocean are performed in the next section.

4. Satellite retrievals

Several theoretical studies for the determination of the aerosol vertical structure using hyperspectral measurements in the oxygen A-band have been performed (e.g. Timofeyev *et al.* 1995, Heidinger 1998, Corradini and Cervino 2006). However, to our knowledge, they were never applied to satellite data. Therefore, this paper presents the application of the technique, for the first time, to the determination of the DTH from hyperspectral measurements performed from a satellite. We have used well-calibrated (Kokhanovsky *et al.* 2008) Processor 6 data of the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), which is one of the ten instruments onboard the European Space Agency (ESA) Environmental Satellite (ENVISAT). It performs measurements in the oxygen A-band with a spectral resolution of 0.48 nm (Gottwald *et al.* 2006). The spatial resolution of SCIMACHY is 30×60 km and also half of the ground pixels are lost due to the limb observation mode (Bovensmann *et al.* 1999). Therefore, it is difficult to select SCIAMACHY pixels that are free of clouds. For a case study, we selected the dust storm of 11 March 2005. The MEdium Resolution Imaging Spectrometer (MERIS) (Bézy *et al.* 2000) browse image is given in figure 7. We have used a visual inspection of this browse image (a spatial resolution of 1.2×1.2 km) to select a cloud-free 1800 km^2 SCIAMACHY scene for the retrieval procedure. The MERIS and the SCIAMACHY are both positioned on the ENVISAT and observe the same ground scenes simultaneously. The corners of the selected scene are given by black squares in

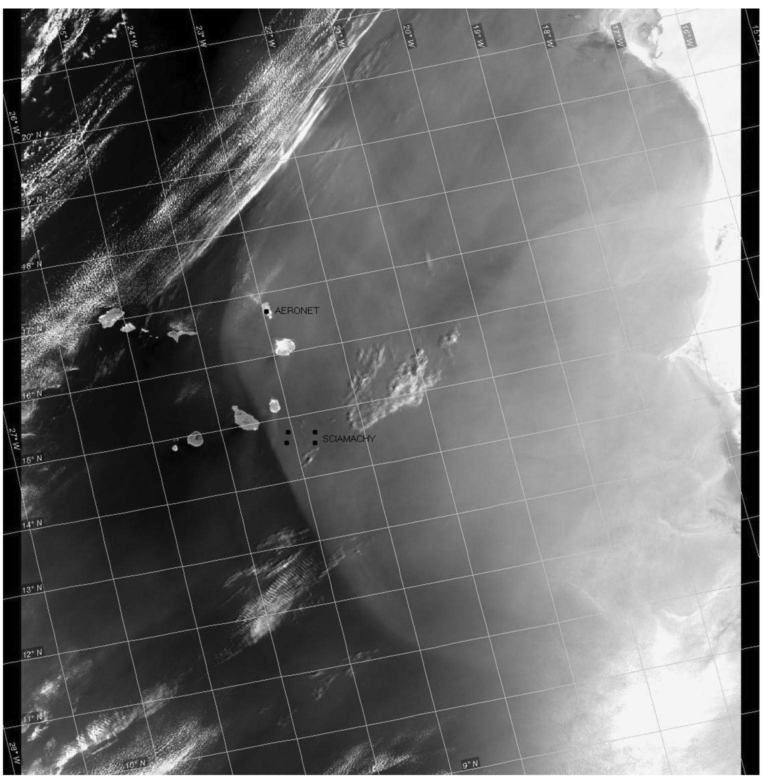


Figure 7. MERIS browse image, west of the coast of Africa. Capo Verde islands we clearly seen in the image. The North corresponds to the upper part of the figure.

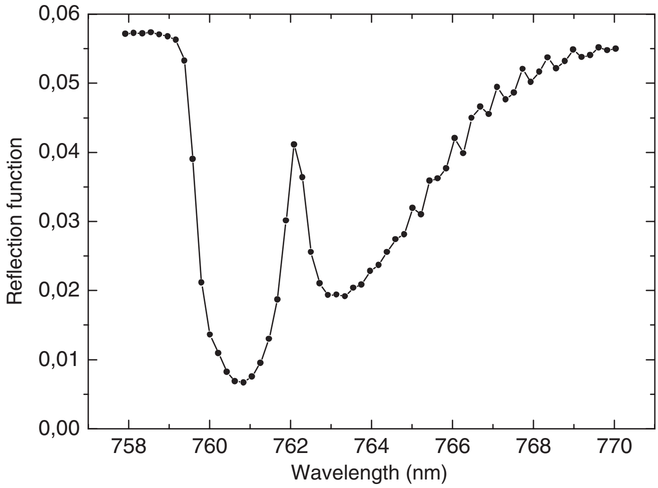


Figure 8. SCIAMACHY TOA spectral reflection function for the 30×60 km pixel located at 22.89° W, 14.59° N for the ENVISAT orbit 15837, 11 March 2005, 11:36 UTC. The solar zenith angle is 38.85°, the solar azimuth is 118°, the observation zenith angle is 9.61° and the observation azimuthal angle is 282.37°. Pluses, SSA = 0.98; circles, SSA = 1.0.

figure 7. Also, the position of the Aerosol Robotic Network (AERONET) site, where the ground-based aerosol optical thickness measurements are performed on a continuous basis, is indicated in the browse image. The corresponding TOA reflectances, as measured by the SCIAMACHY, are presented in figure 8.

The oxygen A-band structure similar to that given in the synthetic spectra shown in figure 1 is clearly seen in the experimental spectrum. For the determination of the DTH, information on the DOT is needed. To increase the accuracy of the retrieval, we have used the theoretical reflectivity generated, not with the Monte Carlo method-derived phase function shown in figure 2, but rather with the experimental phase function measured in Senegal (von Hoyningen-Huene *et al.* 1999) during similar desert-dust conditions shown in figure 7. The calculated dependence of the reflectance on the DOT for this phase function and an SSA = 1.0 is given in figure 9 for the case of an underlying black surface. We obtain $\tau = 0.9$ at $R(758 \text{ nm}) = 0.06$ from this figure, which corresponds well with almost simultaneous sunphotometer measurements ($\tau = 0.94$, see figure 10) performed at Capo Verde, which is a site close to the selected SCIAMACHY ground pixel. Therefore, we are quite confident of the retrieved value of the DOT. The derived value of the DOT suggests that the influence of SSA on retrievals is negligible. Therefore, we assume that $\omega_0 = 1.0$ in the retrieval procedure. The ocean is black in the near-infrared. Therefore, we make retrievals assuming a black underlying ground surface. Yet another assumption is that the dust layer starts from the ocean surface. Using all these assumptions, we ran our algorithm as described above. To reduce errors related to the calibration and other uncertainties related to satellite retrieval algorithms, we performed the inversion for the normalized reflection function $R_n(\lambda) = R_{\text{mes}}(\lambda)/R_{\text{mes}}(758\text{nm})$ and not for the measured (mes) reflectance $R_{\text{mes}}(\lambda)$ shown in figure 8.

The retrieved value of the DTH appeared to be equal to 0.96 km, which is a reasonable number taking into account that retrievals are performed in the front

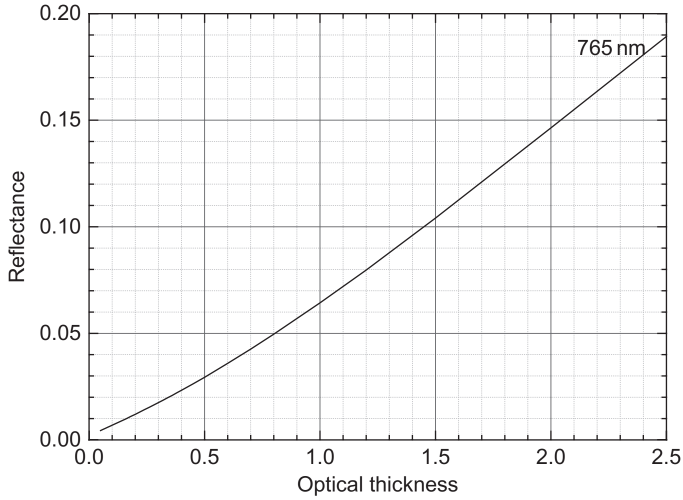


Figure 9. Calculated dependence of reflectance on the optical thickness.

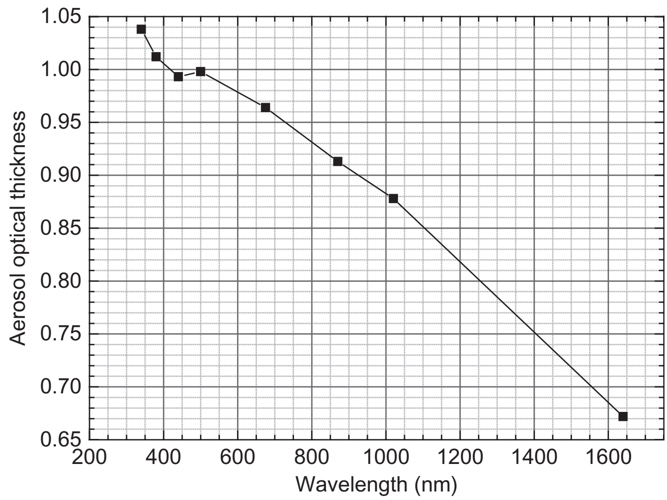
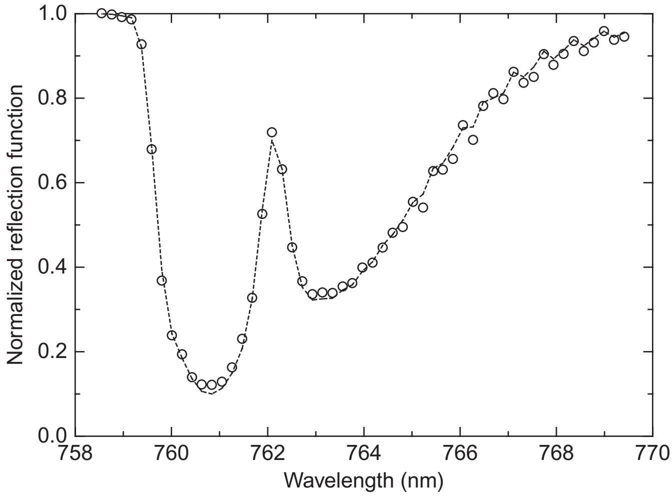


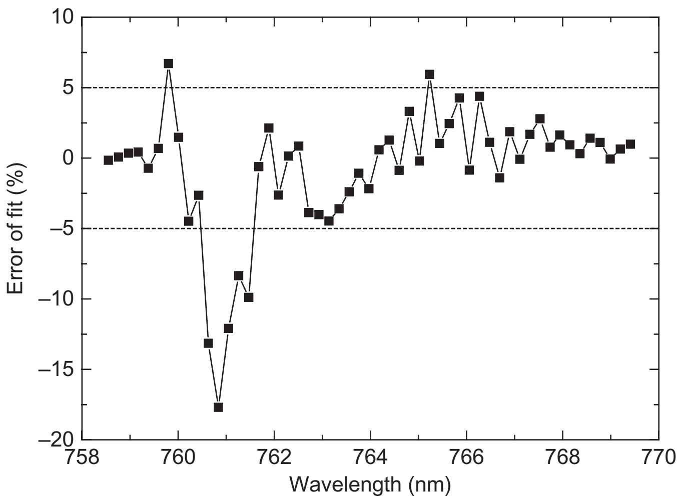
Figure 10. The spectral aerosol optical thickness measured by the AERONET sunphotometer at Capo Verde on 11 March 2005 (11:36:06.77 UTC).

zone of the dust storm (see figure 7). It is also clearly seen from the image that the tropospheric clouds are above the dust storm. The validation of the technique (e.g. using airborne lidars) is needed before large SCIAMACHY databases of the reflectance over dust storms in the oxygen A-band can be processed with this technique. In addition, the extension of the technique to retrievals over bright desert ground is needed. This requires the use of corresponding surface-reflectance databases (around 758 nm).

The accuracy of fit for our retrieval is shown in figure 11. The deviations of the fitted curve and the measurement spectrum in the centre of the band are pronounced



(*a*)



(*b*)

Figure 11. Accuracy of the fit. Symbols in (*a*) show the SCIAMACHY measurements and the broken line corresponds to the final fit found in the iteration process as described in the paper($\tau = 0.9, h = 0.96$km). The error of fit is shown in (*b*)

because the reflection function takes very small values there. Here, both measurement and modelling errors could be quite high.

5. Conclusions

A new numerical technique to determine the DTH from a satellite using oxygen A-band spectrometry is proposed. It is based on the fit of the measured reflectivity in the oxygen A-band to the results of the exact radiative transfer calculations for the assumed dust phase function, the SSA and also the underlying surface reflectance.

The described theory is incorporated in the inversion module of the radiative transfer code SCIATRAN that is available at www.iup.physik.uni-bremen.de.

It was found that theoretical errors of the retrieved dust layer top height do not exceed 150 m for known values of SSA, the surface albedo and the phase function of the vertically homogeneous dust plume. Errors are below 500 m if the SSA used in the retrieval process deviates by not more than 0.01 from the actual value of 0.99. The errors in the retrieved DOT due to unknown values of SSA increase with DOT.

In real applications, the error of the technique to retrieve dust height can be larger due to unknown underlying surface albedo (although they are small in the near-infrared over the ocean), the unknown dust layer vertical structure and also due to uncertainty in the aerosol phase function; therefore, possibly large errors in the retrieved DOT are obtained. The 50% error in the DOT leads to 0.3–0.6 km over-estimation (for too low DOT) or underestimation (for too high DOT) of the DTH. The scenes with the sub-pixel clouds mixed with the dust layer or located below/above the layer must be screened out before the procedure can be applied. We believe that the proposed new method for the dust top determination from a satellite will be proven to be useful in a range of applications. In particular, we have applied the developed technique to the SCIAMACHY onboard the ENVISAT. The spatial resolution of the SCIAMACHY is very limited. Therefore, the technique can greatly benefit from satellite missions such as the Greeenhouse Gases Observing Satellite (GOSAT) (Shiomi *et al.* 2007), which has better spatial and spectral resolution compared to the SCIAMACHY (Bovensmann *et al.* 1999). We plan to quantify uncertainties of the DTH retrieval proposed and performed in this paper using Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (Huang *et al.* 2007) data in our next publication on the topic.

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